Gluon shadowing and hadron production in heavy-ion collisions at LHC

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The recently published first measurement of charged hadron multiplicity density at mid-rapidity $dN_{ch}/d\eta = 1584 \pm 4(\text{stat.}) \pm 76(\text{sys.})$ in central $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV by the ALICE Experiment at LHC is in good agreement with the HIJING2.0 prediction within the experimental errors and theoretical uncertainties. The new data point is used to carry out a combined fit together with the RHIC data to reduce the uncertainty in the gluon shadowing parameter s_g which controls the overall magnitude of gluon shadowing at small fractional momentum x in HIJING2.0 model. Predictions on the centrality dependence of charged hadron multiplicity density at mid-rapidity with reduced uncertainties are given for $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ and 5.5 TeV. The centrality dependence is surprisingly independent of the colliding energy similar to that in $Au + Au$ collisions at RHIC for most of centralities starting at $N_{\text{part}} = 50$ (100) at $\sqrt{s} = 2.76$ (7) TeV. However, it becomes stronger in peripheral collisions at higher colliding energies.

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Bulk observables such as rapidity density of hadron multiplicity and transverse energy provide important information on the initial entropy and energy production in high-energy heavy-ion collisions. They also provide constraints on the initial conditions for hydrodynamical study of the collective phenomenon and hard probes such as jet propagation and suppression. Because of the non-perturbative and many-body nature of the physics processes involved, a first principle calculation of the bulk hadron production is so far unaccessible in Quantum Chromodynamics (QCD). Instead, one has to reply on theoretical and phenomenological models to estimate the bulk hadron production in high-energy heavy-ion collisions. Even with constraints by experimental data from the Relativistic Heavy-ion Colliders (RHIC) experiments [1] there still exits large uncertainties in the theoretical and phenomenological estimates of charged hadron multiplicities in heavy-ion collisions at the Large Hadron Collider (LHC) both among different models and within each model [2].

Recently, ALICE Experiment at LHC published the first experimental data on the charged hadron multiplicity density at mid-rapidity in central $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV [3]. The measured $dN_{ch}/d\eta = 1584 \pm 4(\text{stat.}) \pm 76(\text{sys.})$ for the top 5% central $Pb+Pb$ collisions is larger than most of theoretical and phenomenological predictions, including all the latest color-glass-condensate model calculations [3]. Such an unexpected large hadron multiplicity will have important implications on the underlying mechanism for initial parton production. It will also have important consequences on the study of other phenomena such as collective flow and jet quenching in $Pb + Pb$ collisions at the LHC energies since they all depend on the initial condition for the bulk matter evolution.

The first ALICE data [3] is in good agreement with the HIJING2.0 prediction [4, 5] within the experimental errors and theoretical uncertainty which is controlled mainly by the uncertainty in the parameterization of the unknown nuclear shadowing of gluon distribution. The new HIJING parameterization of the gluon shadowing in nuclei [4] was constrained mainly by experimental data on charged hadron multiplicity and its energy and centrality dependence in heavy-ion collisions at RHIC within HIJING2.0 [5] model which is an updated version of the original HIJING1.0 model [6, 7]. At the LHC energies, initial parton production probes gluon distribution at much smaller fractional momentum x. The range of the gluon shadowing parameter $s_g = 0.17 - 0.22$ allowed by the RHIC data, which controls the overall magnitude of the gluon shadowing at small x in the new HIJING parametrization, leads to much larger uncertainties in the final charged hadron multiplicity, up to about 15% in the most central $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV [5]. Within the same HIJING2.0 model, the ALICE data provides a much stringent constraint on the gluon shadowing. In this note, we will carry out a global fit of the combined RHIC data on the centrality dependence of charged hadron multiplicity in $Au + Au$ collisions and the new ALICE data in the most central $Pb + Pb$ collisions at LHC to provide a better constraint on the gluon shadowing parameter s_g. With a smaller range of the gluon shadowing parameter $s_g = 0.20 - 0.23$, we will predict with reduced uncertainty the centrality dependence of charged hadron multiplicity density in mid-rapidity for $Pb + Pb$ collisions at both $\sqrt{s} = 2.76$ and 5.5 TeV.

HIJING [6, 7] is essentially a two-component model for hadron production in high energy nucleon [8–10] and nuclear collisions [11, 12]. In this two-component model, one divides nucleon interaction into soft and hard part separated by a cut-off p_0 in the transverse momentum transfer between colliding partons. Jet production with transverse momentum $p_T > p_0$ can be calculated within the collinear factorized perturbative QCD (pQCD) parton model while the soft interaction is characterized by a parameter in the effective cross section σ_{soft}. These two parameters, σ_{soft} and p_0 in HIJING, are determined phenomenologically by fitting the experimental data on total cross sections and hadron multiplicity in $p+p/\bar{p}$ collisions [13]. HIJING2.0 [5] is an updated version in which old Duke-Own (DO) parameterization [14] of parton distribution functions (PDF's) is replaced by the Gluck-Reya-Vogt(GRV) parameterization [15]. Because of the much larger gluon distribution in GRV than DO parameterization at small x, one has to assume an energy-dependent cut-off $p_0(\sqrt{s})$ and soft cross section $\sigma_{soft}(\sqrt{s})$ [5] in order to fit the experimental values of the total and inelastic cross sections of $p+p/(\bar{p})$ collisions. The values of p_0 and σ_{soft} are further constrained by the energy-dependence of the central rapidity density of the charged hadron multiplicities. This updated version HIJING2.0 can describe most of the features of hadron production in pp collisions at colliding energies up to 7 TeV at LHC [13].

For high-energy heavy-ion collisions, both nuclear modification of the parton distribution functions and jet quenching in final state interaction have to be considered. Jet quenching in general suppresses high transverse momentum hadrons [16]. If we assume the effects of parton and hadron final state interactions on the total hadron multiplicity to be negligible [17–19], the only uncertainty for hadron multiplicity density in $A+A$ collisions comes from the nuclear modification of parton distribution functions at small x. HIJING2.0 employes the factorized form of parton distributions in nuclei,

$$f_a^A(x,Q^2) = AR_a^A(x,Q^2)f_a^N(x,Q^2), \qquad (1)$$

where $R_a^A(x,Q^2)$ is nuclear modification factor as given by the new HIJING parameterization [4],

$$\begin{aligned} R_q^A(x,b) &= 1.0 + 1.19\log^{1/6}\!A\;(x^3 - 1.2x^2 + 0.21x) \\ &- s_q(b)\;(A^{1/3}-1)^{0.6}(1-3.5\sqrt{x}) \\ &\times\; \exp(-x^2/0.01), \qquad (2) \\ R_g^A(x,b) &= 1.0 + 1.19\log^{1/6}\!A\;(x^3 - 1.2x^2 + 0.21x) \\ &- s_g(b)\;(A^{1/3}-1)^{0.6}(1-1.5x^{0.35}) \\ &\times\; \exp(-x^2/0.004), \qquad (3) \end{aligned}$$

for quarks and gluons, respectively. The impact-parameter dependence of the shadowing is implemented through the parameters,

$$s_a(b) = s_a\frac{5}{3}(1-b^2/R_A^2), \qquad (4)$$

where $R_A = 1.12A^{1/3}$ is the nuclear size. Such factorized form of nuclear modification has been studied with data from deeply inelastic scattering (DIS) and Drell-Yan lepton pair production experiments [20, 21]. However, gluon shadowing at small x is not constrained in these experiments. In the new HIJNG parametrization, the value $s_q = 0.1$ is fixed by the experimental data on DIS off nuclear targets [4]. The value of gluon shadowing parameter s_g is constrained only by the hadron multiplicity in heavy-ion collisions. Using the combined RHIC data [1] on the centrality dependence of charged hadron multiplicity density in mid-rapidity as constraints, a range $s_g = 0.17-0.22$ was obtained [5]. The form of the impact parameter dependence is chosen to give rise to the centrality dependence of the pesudorapidity multiplicity density per participant pair $2dN_{ch}/d\eta/N_{\rm part}$.

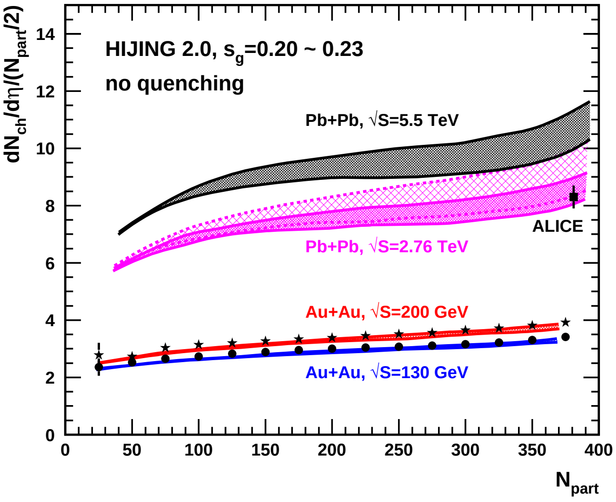

FIG. 1: (color online) Charged hadron multiplicity density in mid-rapidity per participant pair $2dN_{ch}/d\eta/N_{\rm part}$ as a function of $N_{\rm part}$ from HIJING2.0 calculation with gluon shadowing parameter $s_g = 0.20-0.23$ (solid-shade) and $s_g = 0.17-0.22$ (dash-shade) as compared to combined RHIC data [1] for $Au+Au$ collisions (filled circle and star) and ALICE data [3] at LHC (solid square).

With the above parameterization of parton shadowing and the range of gluon shadowing parameter $s_g = 0.17-0.22$, the predicted $2dN_{ch}/d\eta/N_{\rm part}$, shown as dash-shaded area in Fig. 1, agrees well with the new ALICE data in the most central $Pb+Pb$ collisions at $\sqrt{s} = 2.76$ TeV, within the experimental error and a large theoretical uncertainty of about 15% from the gluon shadowing parameter. The HIJING2.0 results are obtained by calculating $dN_{ch}/d\eta$ and $N_{\rm part}$ for different impact-parameters squared b^2 with equal bin size. By performing a combined χ^2-fit of the RHIC data [1] for $Au+Au$ collisions at $\sqrt{s} = 200$ GeV and the data point from ALICE in the most central $Pb+Pb$ collisions at $\sqrt{s} = 2.76$ TeV, the range of gluon shadowing parameter is reduced to $s_g = 0.20-0.23$. With this new range of s_g and therefore reduced uncertainty we calculate the prediction for the centrality dependence of $dN_{ch}/d\eta$ in $Pb+Pb$ collisions at both $\sqrt{s} = 2.76$ and 5.5 TeV, shown in Fig. 1, as solid-shaded area. The calculated centrality dependence of $dN_{ch}/d\eta$ in $Au+Au$ collisions at two RHIC energies is also shown together with combined RHIC data [1].

To exam the centrality dependence of $dN_{ch}/d\eta$ at different colliding energies in detail, we plot in Fig. 2 the

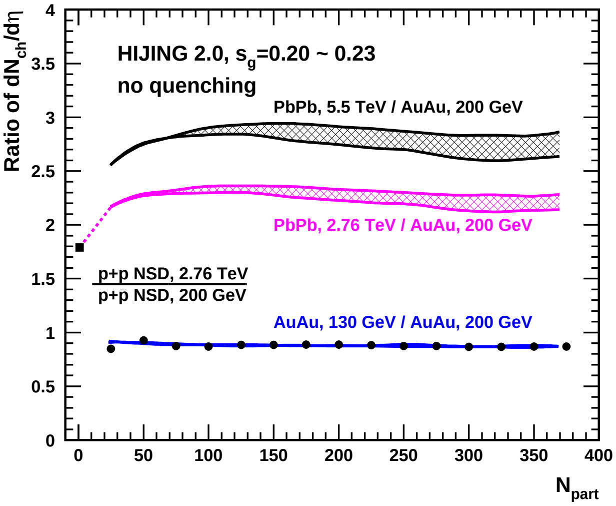

FIG. 2: (color online) The ratio of charged hadron multiplicity density in mid-rapidity in heavy-ion collisions at different colliding energies, using $Au+Au$ collisions at $\sqrt{s}=200$ GeV as the common denominator. The data at the RHIC energies are combined from different experiments [1]. The ALICE data on non-single diffractive (NSD) pp collisions at $\sqrt{s}=2.36$ TEV [22] is used to get the data point at $\sqrt{s}=2.76$ TeV using HIJING2.0 extrapolation. The NSD $p\bar{p}$ data at $\sqrt{s}=0.2$ TeV is from UA1 [23]

ratio of $dN_{ch}/d\eta$ at different colliding energies using $Au+Au$ collisions at $\sqrt{s}=0.2$ TeV as the common denominator. In the figure we also plot (pp 2.76 TeV)/($p\bar{p}$ 0.2 TeV), using the ALICE data on non-single diffractive pp collisions at $\sqrt{s}=2.36$ TeV [22] and HIJING2.0 calculation to extrapolate to the value at $\sqrt{s}=2.76$ TeV. The $p\bar{p}$ data at $\sqrt{s}=0.2$ TeV is from UA1 [23]. The ratios of charged hadron multiplicity densities at the two LHC energies to that at RHIC are surprisingly flat over a large range of centralities just as the ratio of two RHIC energies. It is interesting to note that the increased energy dependence of charged multiplicity density in central $Pb+Pb$ collisions over that in pp is reached already at $N_{\rm part}=50(100)$ for $\sqrt{s}=2.76$ (5.5) TeV. In other words, the centrality dependence of charged hadron multiplicity density increases with energy in peripheral $Pb+Pb$ collisions. Such centrality dependence of charged hadron is a consequence of the impact-parameter-dependent gluon shadowing in HIJING2.0.

With a given transverse momentum cut-off p_0, the total number of mini-jets per unit transverse area could become so large that it exceeds the limit

$$\frac{T_{AA}(b)\sigma_{jet}}{\pi R_A^2} \leq \frac{p_0^2}{\pi} \tag{5}$$

for independent multiple jet production for sufficiently large inclusive jet cross section at high colliding energies and for large nuclei, where $T_{AA}(b)$ is the overlap function of $A+A$ collisions and π/p_0^2 is the intrinsic transverse size of a mini-jet with transverse momentum p_0. This is the reason for an energy-dependent cut-off p_0 for high-energy pp collisions in HIJING2.0 since the GRV parton distributions [15] have a large gluon distribution at small x and therefore large mini-jet cross section at high colliding energies. The above limit for incoherent mini-jet production should also depend on nuclear size and impact-parameter which can be determined self-consistently through Eq. (5) [18]. In HIJING2.0 such impact-parameter dependence of the cut-off scale is not considered. Instead, an impact-parameter dependence of the gluon shadowing in Eq. (4) is considered that is stronger than the typical nuclear length $L_A=\sqrt{R_A^2-b^2}$ dependence. Such a stronger impact-parameter dependence is favored by the centrality dependence of dN_{ch}/η in $Au+Au$ collisions at RHIC. This is also the reason for nearly energy-independence of the centrality dependence of charged hadron multiplicity density at the LHC energies. If confirmed by experimental measurements, it will have important implications on the initial eccentricity for the study of elliptic flow and jet quenching.

In summary, we have carried out a combined fit of the new ALICE data [3] on charged hadron multiplicity density in the most central $Pb+Pb$ collisions at $\sqrt{s}=2.76$ TeV and the RHIC data within HIJING2.0 model. The range of gluon shadowing parameter $s_g=0.20-0.23$ in the new HIJING parameterization of parton shadowing [4] enables us to predict the centrality dependence of the charged hadron rapidity density with reduced uncertainty in $Pb+Pb$ collisions at $\sqrt{s}=2.76$ and 5.5 TeV. The centrality dependence is surprisingly independent of colliding energy for most centralities starting at $N_{\rm part}=50$ (100) for $\sqrt{s}$=2.76 (5.5) TeV. However, the centrality dependence in the peripheral collisions becomes stronger at higher colliding energies.

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